



# Tribological Performance of PM300 Solid Lubricant Bushings for High Temperature Applications

*Donald R. Striebing*

*U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio*

*Malcolm K. Stanford and Christopher DellaCorte*

*Glenn Research Center, Cleveland, Ohio*

*Anne M. Rossi*

*Case Western Reserve University, Cleveland, Ohio*

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National Aeronautics and  
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Glenn Research Center  
Cleveland, Ohio 44135

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Donald R. Striebing  
U.S. Army Research Laboratory  
Glenn Research Center  
Cleveland, Ohio 44135

Malcolm Stanford and Christopher DellaCorte  
National Aeronautics and Space Administration  
Glenn Research Center  
Cleveland, Ohio 44135

Anne M. Yanke  
Case Western Reserve University  
Cleveland, Ohio 44106

## **Abstract**

PM300 is a high temperature solid lubricant material produced through conventional powder metallurgy processing. PM300 is a combination of metal binder (NiCr), hardener ( $\text{Cr}_2\text{O}_3$ ) and lubricant (Ag and  $\text{BaF}_2/\text{CaF}_2$ ) phases and is in commercial use in high temperature furnace conveyors. In this paper, the tribological characteristics of PM300 are evaluated using a newly developed bushing test rig in which PM300 bushings are loaded against rotating steel shafts at temperatures from 25 to 650 °C. The data shows that friction and wear are low to moderate and that the lubrication performance (friction) improves with increasing temperature. Several alternative PM300 compositions are evaluated which do not contain silver and are targeted at aircraft gas turbine applications in which environmental compatibility of silver is a concern. It is expected that the data resulting from this research will further the commercialization of this technology.

## **Introduction**

Plain cylindrical bushings are often used in sliding contacts to lubricate simple mechanisms. These bushings are commonly made from porous bronze infiltrated with oil and have been in widespread use for over a century. For more demanding applications, especially temperatures over 100 °C, solid lubricant materials are used such as graphite, PTFE, and other polymers. Often, composite materials made from metals, polymers and ceramics with solid lubricant fillers or pigments, are employed. These types of bushings are suitable for use at temperatures below about 300 °C. Proprietary compounds may extend this use temperature up to and even beyond 500 °C for limited exposure times. However, generally speaking, conventional solid lubricant materials cannot operate reliably above 500 °C (ref. 1). For these temperatures novel approaches must be considered.

One approach employed at the authors' laboratory is to combine thermochemically stable solid lubricants with metal bonded cermets and ceramics to form a composite material. By selecting solid lubricant additives that function over a wide range of temperatures, a composite material can be formed which combines the tribological properties of its constituents. One such material system developed by Sliney is the PS/PM200 system. This composite contains a nickel-cobalt bonded chromium carbide matrix with about 10 to 15 percent each of silver and barium-calcium fluoride. The matrix offers strength and wear resistance and the silver and fluoride constituents offer low and high temperature solid lubrication respectively (ref. 2).

This nickel-cobalt-carbide materials system was originally developed as a coating deposited by plasma spray and designated PS200. Subsequently, it was manufactured via powder metallurgy processing as a free standing composite material, PM200 (refs. 2 and 3). Considerable development work was done on both the coating (PS200) and the powder metallurgy (PM200) forms of the material. This work included the determination of tribological properties, thermo-physical properties and environmental durability (ref. 4).

Unfortunately, the PS/PM200 materials system never achieved widespread commercialization. One reason was inherently high costs. The starting material, namely the cobalt bonded carbide, is expensive. Further, the chrome carbide phase could not be effectively machined unless diamond tools were used. This increased manufacturing costs considerably. In addition, in sliding, the carbide phase often caused excessive wear of the counter face material necessitating the use of high performance alloy mating surfaces in order to achieve long life. These shortcomings of the PS/PM200 materials system provided the impetus for the development of a new family of tribomaterials, PS/PM300.

Like its predecessor, the new material system PM300, was first developed as a plasma spray deposited coating PS300. PS300 contains 60 wt% chrome oxide, 20 wt% nickel-chrome with 10 wt% each of silver and barium-calcium fluoride solid lubricant additives (ref. 5). Initial data on PS300 showed that it had good tribological properties and was readily finished with low cost carbide tools (refs. 6 and 7). However, more in depth research studies identified a serious drawback for this new materials system; an unexpectedly low thermal expansion coefficient (ref. 8). After several thermal cycles above 500 °C, the original PS300 coating formulation would crack and spall off of its superalloy substrate. Subsequent research identified a family of alternate compositions with a wide and controllable range of thermal expansion coefficients to match many candidate substrate alloys. One composition in particular, designated PS304, contained 60 wt% nickel chrome binder, 20 wt% chrome oxide as a hardening additive, and 10 wt% each of the solid lubricants silver and fluoride. PS304 exhibits a thermal expansion coefficient similar to most nickel based superalloys. PS304 has been found to be useful as a shaft lubricant coating for foil gas bearings and as a valve stem lubricant for steam turbine control valves (refs. 9 and 10).

Despite the initial commercial success of the PS304 coating, many applications exist in which it is inconvenient or impractical to use a thermal spray coating. Thermal spray coatings cannot generally be applied to small inside diameters (like bushings) and their need for finish grinding adds overall expense. In these instances, powder metallurgy is a better production route. Following the development path of the PS/PM200 system, the PS304 materials system was produced via powder metallurgy processing techniques. The following paper describes the starting materials and the powder metallurgy processing path. Bushings developed for an industrial furnace conveyor application are then tested to quantify their tribological properties. These will be compared to conventional bushing materials and additional applications, like gas turbine inlet guide vane bushings, will be discussed. For clarity and future simplicity, the powder metallurgy composite described in this paper is designated PM300, not PM304 even though its composition matches PS304, not the original PS300.

## **PM300 Materials**

PM300 consists of 60 wt% nickel chrome (NiCr), 20 wt% chromium oxide and 10 wt% each of silver and barium-calcium fluoride eutectic. Table I shows the exact composition of each constituent and their function in the composite. NiCr is selected as the binder because of its excellent thermal and oxidative stability, its availability as a free flowing powder and its low cost. Chrome oxide is used as a hardening agent and, because it is already fully oxidized, exhibits excellent environmental stability in high temperature air. The silver constituent provides good low temperature lubrication due to its low shear strength and is oxidatively stable up to its melting point of 961 °C. Despite silver's tendency to tarnish (oxidize) under ambient conditions it does not oxidize above 150 °C. In fact, any silver oxide present on the surface will dissociate in air when heated, reverting the surface to pure silver (ref. 11). The second lubricant additive to PM300 is barium-calcium fluoride eutectic. It is added as a high temperature

lubricant because it shears easily at temperatures above about 400 °C (ref. 12) and is thermo-chemically stable to its melting point of 1086 °C. Figure 1 shows a typical cross section optical micrograph of PM300. The micrograph clearly shows that PM300 is a composite made up of several distinct phases.

## **Materials Processing**

PM300 is made by conventional powder metallurgy processing. The starting material is a powder blend of the constituents listed in Table I. Typical particle sizes for the constituents range from 30 to 70  $\mu\text{m}$ . A simple three step process is used to make PM300. First, PM300 powder is fed into a double acting tool/die. Then a punch is forced against the loose powder in a compaction process. The resulting “green” part is ejected from the die and heated in a hydrogen or vacuum atmosphere at 1100 °C for 20 min to allow liquid (the silver and fluoride both melt) phase sintering to occur. Figure 2 schematically shows these processing steps. During the sintering step, the PM300 part experiences some shrinkage as well as densification.

With proper dimensional design of the die, highly uniform and precise net shape parts can result from the process. Typically, no post sintering machining is required before the parts are put into service. This can lead to dramatic cost savings for a PM300 lubricated mechanism compared to a PS300 coating lubricated mechanism which would require masking and finish grinding steps prior to use. Figure 3 shows PM300 test bushings made with the press and sinter process. Diameters and wall thickness variations are typically less than 0.05 mm making them ideal for many industrial applications. For the present study, PM300 bushings originally developed for an industrial furnace application are used. Figure 4 gives their nominal dimensions.

## **Test Rig Description**

The PM300 bushings are tested in sliding in a high temperature bushing test rig. For the present work, the bushings are loaded against a rotating (low carbon, 1010) steel shaft. Figure 5 is a photograph of the test rig. The bushings are pressed into a ring or holder which is connected to a rod used to transmit a static load to the bushing. The test load is generated with a pneumatic cylinder and a calibrated electronic load cell positioned between the load cylinder and the load rod provides an accurate and continuous readout of the applied load.

The shaft is mounted in a variable speed lathe chuck driven through a gearbox by an electric motor. The shaft is supported by greased pillow block bushings and is connected to the gearbox with an electronic torque measuring coupling. The motor is capable of driving the shaft at speeds from 10 to 400 rpm which, for the 35 mm diameter shafts translates to a maximum sliding velocity of 0.73 m/s. During development of this rig, careful measurements were made of the parasitic friction in the pillow block bearings which support the test shaft. These were found to be minimal (less than 130 mN-m) at all test loads and speeds. Therefore, the torque measured via the electronic coupling represents an accurate measure of the bearing torque. A chart recorder is used to measure the load and the bearing friction (torque). To produce graphs and plots of the data, samples are taken from the chart recordings typically every 5 min during a 2 hr test.

For high temperature testing, the test specimens are located inside a well insulated, approximately 1.44 kW, clamshell type electric resistance furnace. The furnace has been modified with two holes. One allows the penetration of the test shaft while the other smaller hole, located orthogonally to the first, allows passage of the load rod. The furnace is controlled with a silicon controlled rectifier (SCR) coupled with a Proportional Integral Derivative (PID) controller. A thermocouple placed in the test section is used to monitor test temperature.

## Test Procedure

Prior to testing, the test shaft is mounted into the rig's four jaw type lathe chuck and aligned until the total indicated run-out is below 0.1 mm. Then the shaft surface is cleaned with ethyl alcohol and air dried. The PM300 test bushing is pressed into its superalloy holder ring with a slight interference (about 0.05 mm) fit. The bushing-holder assembly is fitted over the end of the shaft and the load rod is connected to the bottom of the holder. The top half of the furnace is then closed and the test is begun by turning on the chart recorder, starting the motor drive and then pressuring the pneumatic loading cylinder until the desired test load is achieved. For high temperature tests, the furnace is powered before turning on the drive motor. When the desired test temperature is achieved the motor is started, the load is applied and testing is begun. All tests are run in ambient lab air which varied in temperature from 20 to 25 °C with relative humidity ranging from 30 to 70 percent.

PM300 bushings of the size reported upon in this paper are currently in commercial service for furnace conveyor components operating from 25 to 550 °C under variable loads of 40 to 100 N at speeds ranging from about 5 to 50 rpm (0.009 to 0.09 m/s). To approximately simulate these conditions and yet accelerate the wear process the following test conditions were initially selected: load 200 N; speed 100 rpm (0.183 m/s), temperature 25 °C. Under these initial test conditions, the bushings immediately failed and disintegrated as shown in the photograph in figure 6. To understand this poor performance, tribological results previously generated with the PS304 coating were reviewed.

These PS304 coating results showed that good tribological properties are only achieved after a break-in process at high temperature during which a lubricious surface glaze forms on the PS304 and also transfers to the counter-face (ref. 13). These advantageous glazes are comprised mainly of the solid lubricant additives in PS/PM300, namely fluorides and silver. Based upon this information, it was decided to reduce the load to 90 N and increase the speed to 200 rpm (0.366 m/s) to promote localized surface heating and the formation of lubricious surface glazes. These new test conditions did not result in bushing disintegration although the measured friction at temperatures below 150 °C was high during the first hour or so of sliding. To fully characterize the PM300 at each test temperature, four 2 hr tests (at 90 N load, 200 rpm) were run for each bushing/shaft combination making for an 8 hr test sequence. Further, four repeat eight hour test sequences were run for each test temperature to assess data scatter and repeatability.

## Results and Discussion

A series of eight test sequences, each consisting of four 2 hr tests, were conducted with temperatures ranging from ambient to 540 °C. At low temperatures (<300 °C), the tribological behavior of the bushing/shaft sliding contact was erratic with a wide friction band and high torque. At high temperatures, the tests ran smoother with relatively low torque. The resulting data can be seen in figure 7. In this figure, each discrete data point represents the average of four 2 hr test runs on one PM300/steel shaft specimen set. Although the friction is quite high at the lower temperatures (typically 0.60 to 0.80), it steadily decreases with increasing temperature to a value of approximately 0.30 at temperatures above 500 °C.

To determine data scatter and repeatability, the same series of PM300 tests was conducted using a bushing/shaft specimen set that had been slid previously at high temperature ( $\geq 500$  °C). The results of the two tests differ greatly, as seen in figure 8. This difference can be attributed to a "break-in" phenomenon. While sliding at high temperatures in the first series of tests the PM300 and steel shaft developed a lubricious surface glaze which lowered friction and wear in the subsequent repeated tests. The repeat tests had much lower and more stable friction values, ranging from 0.30 to 0.36. This "break-in" behavior closely resembles the characteristics of the PS304 coating and was not an unexpected result (ref. 3).

To obtain a better understanding of the PM300 results, two common bushing materials, bronze and graphite, were tested under similar conditions and compared to the PM300 friction data. The bronze and graphite tests were run at 200 rpm (0.366 m/s) with a 90 N load. The test temperatures ranged from ambient to 540 °C. As seen in figure 9, the bronze and graphite bushings showed results, as expected, with low friction, ranging from 0.19 to 0.27. It is also clear that following a suitable break-in period,



PM300 exhibits comparable friction to conventional bushing tribomaterials. However, conventional materials lack the long term high temperature physical and chemical stability inherent in the PM300 material.

In some applications, it may not be practical to perform a high temperature break-in procedure for PM300. In these cases, a sacrificial solid lubricant like graphite may be used on the inside diameter of the PM300 bushing. This could provide temporary lubrication until the surfaces of the PM300 bushing and its counter-face develop a lubricious glaze. This approach is used successfully for PS304 coatings in foil air bearings (ref. 13) and will be explored through additional bushing tests.

As another comparison, figure 10 plots data for PS304, the plasma sprayed coating, along with PM300, after break-in. The data compare well with friction in the range of 0.26 to 0.35. This is a good indication that the tribological characteristics of PM300 are very similar to the coating form of the material.

Figure 11 plots friction data for bushings in which the silver constituent has been replaced with copper, designated PM300-Cu. This composition was selected to enable the use of PM300 type bushings in gas turbines where corrosion reactions between silver and sulphur (from fuels) are potentially a concern. These new specimens were manufactured half the axial length (width) of the previous specimens tested causing the unit area load to be twice that of the standard width PM300 bushing specimens. To accelerate wear, the PM300-Cu bushing tests were run under a 200 N load at 200 rpm (0.366 m/s), 90 N load, at temperatures ranging from ambient to 540 °C. The friction of the PM300-Cu ranged from 0.55 to 0.65; almost double that of the PM300-Rerun but not quite as high as the original PM300 friction.

To better understand the high friction for PM300-Cu a series of parametric tests were conducted for the baseline PM300 composition under a variety of test speeds and (unit) loads. The results are summarized in table II and selected data is presented in figures 12 and 13. From the data it can be seen that the friction for PM300 at 540 °C remains low and constant at ~0.25 at 100 and 200 rpm but increases to 0.4 at 300 and 400 rpm. When the test load is increased a similar effect is observed. Friction coefficients for 100 and 200 N loads are similar, around 0.25, but climb to 0.4 at 300 N and 0.5 at 400 N.

Interestingly, under a 400 N load, the standard PM300 bushing unit load is equivalent to the narrower PM300-Cu bushing under the 90 N load plotted in figure 14. For the same temperature, 540 °C, PM300-Cu friction coefficient was 0.55 which compares favorably with the 0.5 measured for PM300 under the same unit loading. This suggests that, under comparable unit loading, PM300-Cu exhibits similar friction properties to PM300 despite the compositional change to the low temperature lubricant. More work is needed to fully characterize this composition.

The wear of the steel shafts slid against PM300 bushings is shown in table III. The same data is plotted in figure 15. These measurements were made using a stylus surface profilometer traversed across the wear tracks at four locations following the last of the four 8 hr tests. The wear tracks had very uniform wear depths as shown in figure 16. For simplicity, wear of the shafts are presented in the form of wear track depths. Wear volumes can be calculated as the average wear depth multiplied by the track width and circumference. The data shows that shaft wear depth initially rose with temperature up to about 200 °C then dropped considerably especially at test temperatures above 400 °C. The initially observed increase may have been due to the softening of the steel followed by a drop in wear once the lubricious glaze from the lubricants in the PM300 begin to function at test temperatures above 200 °C.

PM300 bushing wear, in these limited duration tests, was too small to accurately measure using conventional techniques. Weight change could not be used because at high temperatures gain due to bushing oxidation confounds any material removal due to wear. Even at room temperature wear was below detectable limits. Longer duration tests are planned to better quantify bushing wear. Possibly higher loads and speeds will be required to increase bushing wear to more readily measurable limits.

## **Concluding Remarks**

These preliminary tests performed on the PM300 bushings have provided promising results for the use of these bushings in future applications. After the implementation of a break in period at high

temperatures, the PM300 bushing friction showed to be only slightly higher than that of the more common, yet less stable, bushing materials such as graphite and bronze. This indicates that the PM300 bushings could be quite useful in a high temperature environment without the need for a cooling mechanism of any kind.

The friction behavior of PM300 is similar to its coating version counterpart, PS304. This comparability suggests that the solid lubricant additives have a significant effect on performance and that the specific material structure play, perhaps, a secondary importance. The PM300 results also corroborate previous experience with the PS304 coating in that good tribological performance results only after the formation of a lubricating surface film or glaze on the sliding surfaces. Future research may be undertaken to develop a sacrificial solid lubricant overlay to allow bushing use without the break-in period. For PS304 coatings, a simple graphite or molybdenum disulphide overlay coating has been found to be effective.

The PM300-Cu bushing tests indicate two major findings. One is that replacement of the low temperature lubricant, silver, with a different soft metal, copper, yields similar tribological behavior. Thus, PM300 compositional tailoring for specific environments is a viable approach. Second, the relatively high friction for the PM300-Cu was attributed to the high unit loading compared to the baseline PM300 tests. This result suggests that the lubricating action of PM300 composites may be limited to low or moderate unit loads and warrants further research. These initial tests of PM300 and PM300-Cu indicate that a variety of high temperature sliding components can be effectively lubricated using this technology. Friction and wear performance comparable to conventional bushing materials is achievable using these tribomaterials and higher temperature, long-term tribological performance is possible.

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TABLE I.—PM300 COMPOSITION SUMMARY

Constituent	wt%	Melting point, °C	Particle size range, $\mu\text{m}$	Function
NiCr <sup>a</sup>	60	1400	44 to 74	Binder
Cr <sub>2</sub> O <sub>3</sub>	20	2435	30 to 44	Hardener phase
Ag	10	960	45 to 100	Low temperature lubricant
BaF <sub>2</sub> /CaF <sub>2</sub> <sup>b</sup>	10	1086	44 to 100	High temperature lubricant

<sup>a</sup>80 wt% Nickel, 20 wt% Chromium

<sup>b</sup>62 wt% BaF<sub>2</sub>, 38 wt% CaF<sub>2</sub>

TABLE II.—FRICTION DATA SUMMARY FOR PM300 AT VARYING LOADS AND SPEEDS AT 540 °C

Value	Constant speed tests				Constant load tests			
Load, N	100	200	300	400	100	100	100	100
Speed, rpm	200	200	200	200	100	200	300	400
Friction	0.3	0.29	0.39	0.52	0.26	0.29	0.39	0.42

TABLE III.—PM300 DIAMETRAL SHAFT WEAR (IN MICRONS) AT VARYING TEST TEMPERATURES

	Test temperature, °C							
Wear <sup>a</sup>	25	148	204	315	371	427	482	540
Shaft wear, $\mu\text{m}$	25	38	50	50	25	5	4	4

<sup>a</sup>90 N load, 200 rpm, aft 4, 2 hr tests

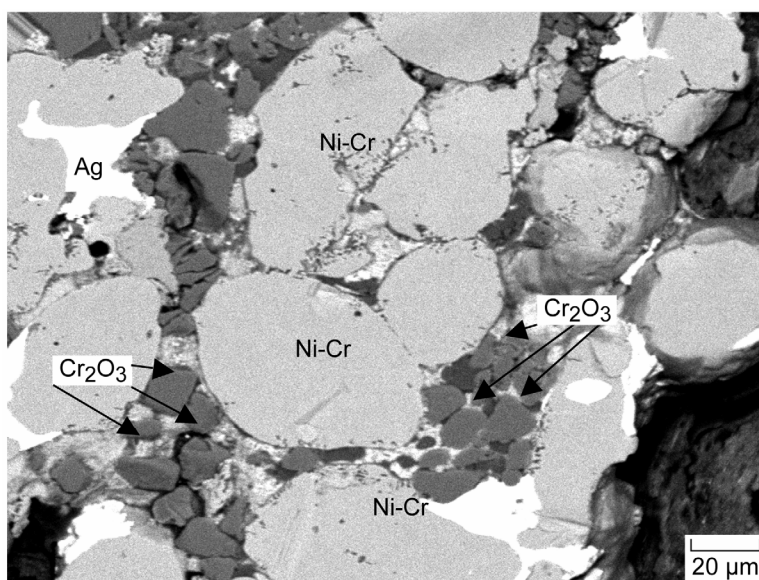


Figure 1.—PM300 typical cross section optical micrograph.

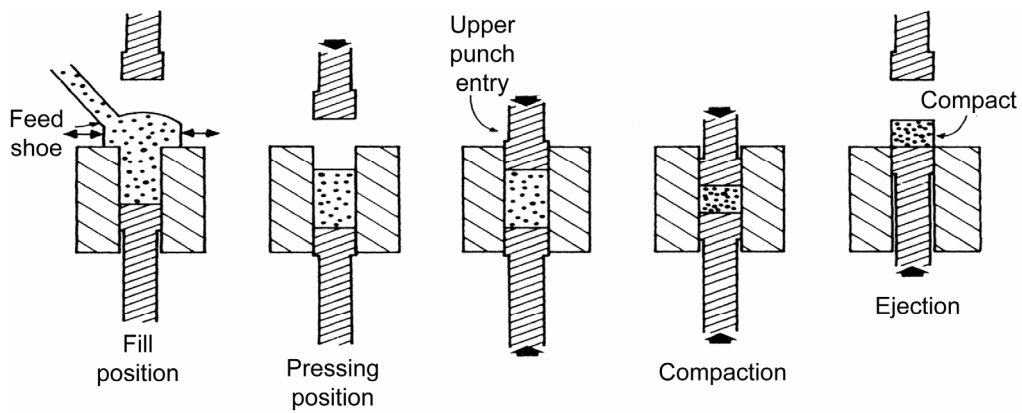


Figure 2.—Powder metallurgy compaction process.



Figure 3.—PM300 test bushings.

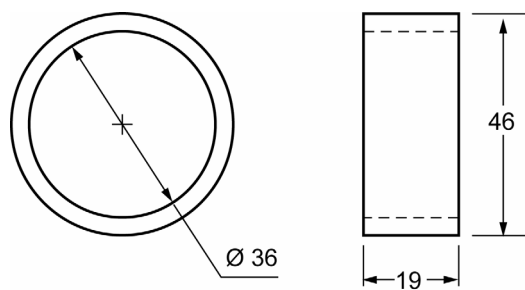


Figure 4.—PM300 nominal test bushing dimensions in mm.



Figure 5.—High temperature PM300 bushing test rig.



Figure 6.—Failed PM300 bushing under initial test conditions.

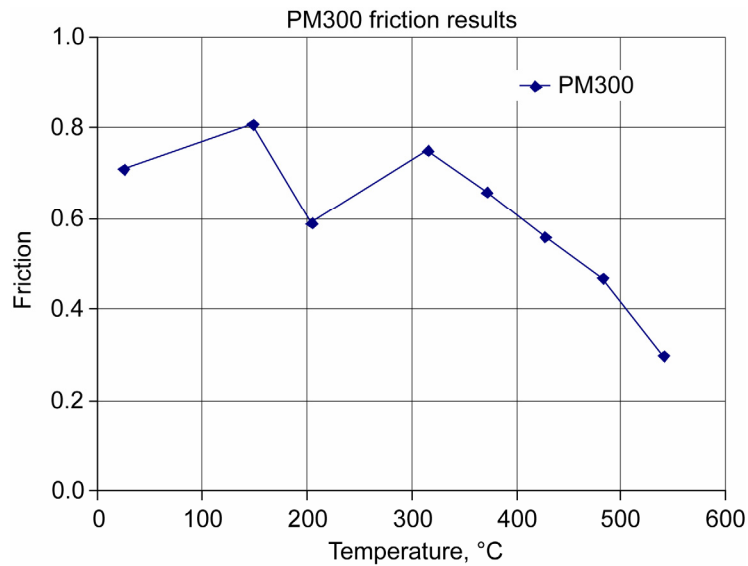


Figure 7.—PM300 test results.

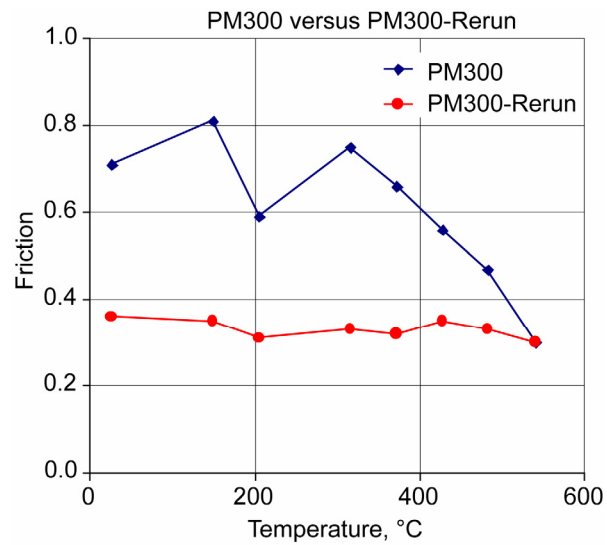


Figure 8.—PM300 results compare to PM300-Rerun test results in which the specimens were previously tested at 500 °C or above.

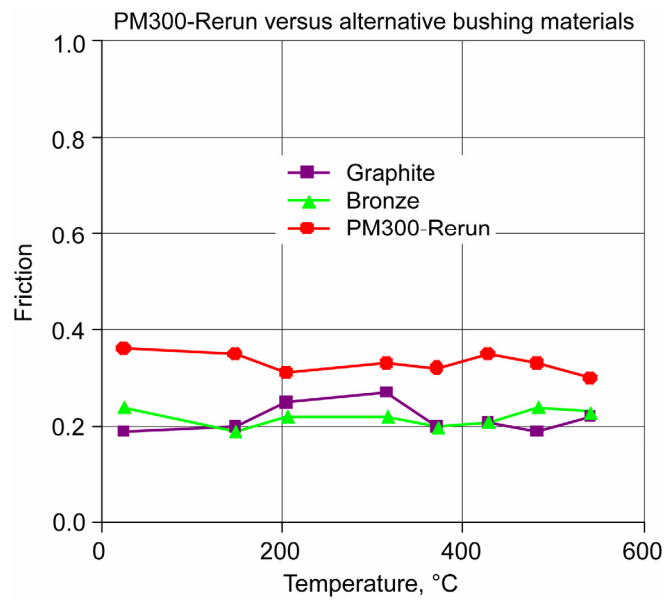


Figure 9.—Comparison of alternative bushing material test results.

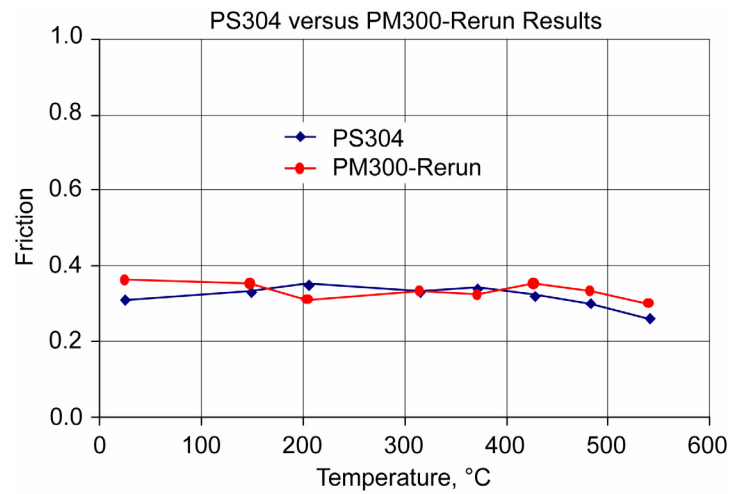


Figure 10.—PM300-Rerun compared with PS304 coating results.

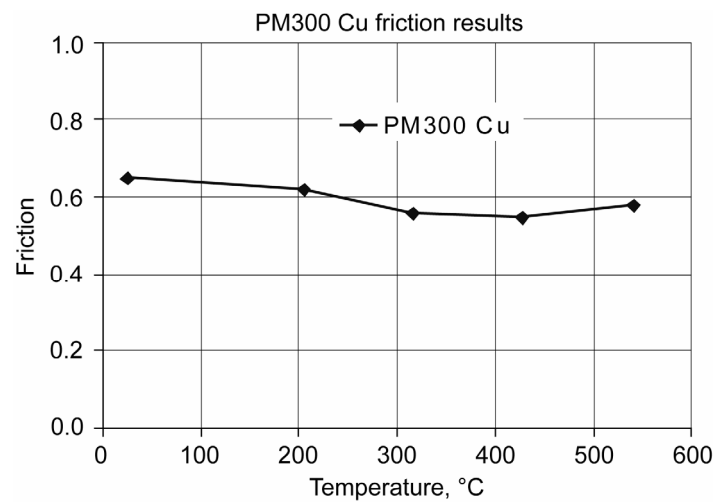


Figure 11.—PM300-Cu friction results.

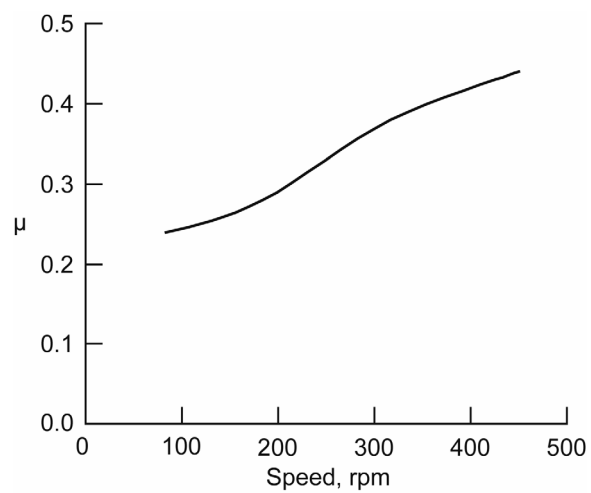


Figure 12.—PM300 friction at varying rotational speeds under a constant 100N load at 540 °C.



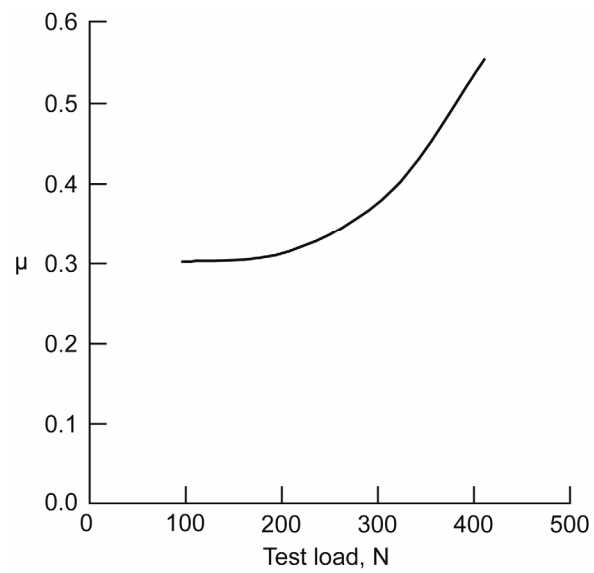


Figure 13.—PM300 friction at varying test loads under a constant speed (200 rpm) and temperature 540 °C.

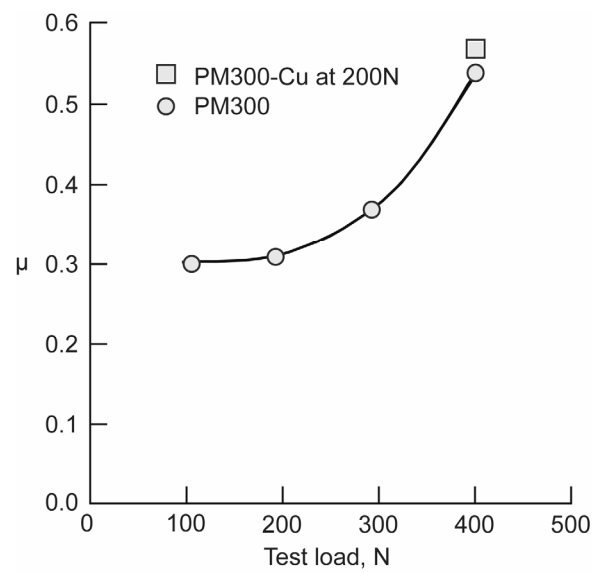


Figure 14.—PM300-Cu data at 200N test load (equivalent unit load for wider PM300 bushing is 400N) compared to PM300 data.

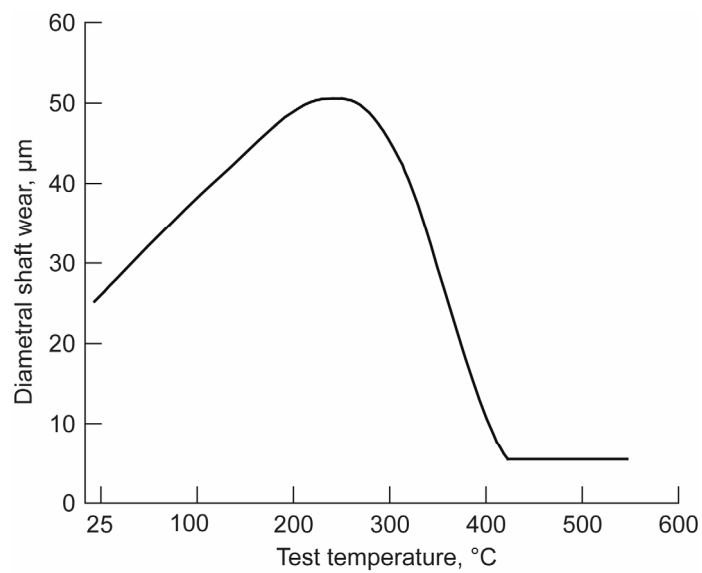


Figure 15.—Diametral steel shaft wear, in microns, following four 2-hour tests against PM300 under 90N load at 200 rpm.

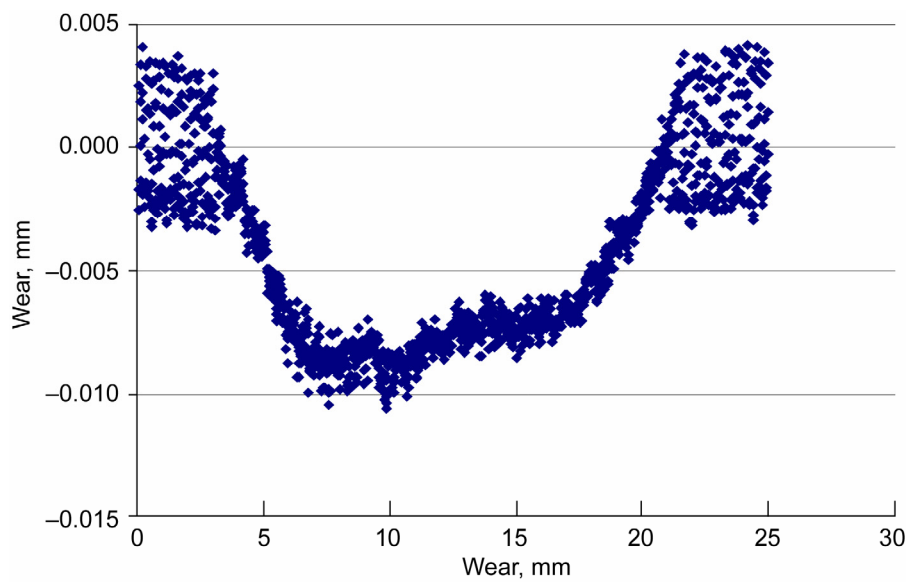


Figure 16.—Diametral shaft wear.

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14. ABSTRACT PM300 is a high temperature solid lubricant material produced through conventional powder metallurgy processing. PM300 is a combination of metal binder (NiCr), hardener (Cr <sub>2</sub> O <sub>3</sub> ) and lubricant (Ag and BaF <sub>2</sub> /CaF <sub>2</sub> ) phases and is in commercial use in high temperature furnace conveyors. In this paper, the tribological characteristics of PM300 are evaluated using a newly developed bushing test rig in which PM300 bushings are loaded against rotating steel shafts at temperatures from 25 to 650 °C. The data shows that friction and wear are low to moderate and that the lubrication performance (friction) improves with increasing temperature. Several alternative PM300 compositions are evaluated which do not contain silver and are targeted at aircraft gas turbine applications in which environmental compatibility of silver is a concern. It is expected that the data resulting from this research will further the commercialization of this technology.					
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